

**Final Report — Summary of Research**  
**NASA Grant NNG04GG62G**  
**New Inquiry into Distribution and Mechanism of Deep Moonquakes with**  
**Recently Identified Seismic Events**

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Period Covered: 1 April 2004 - 31 March 2005

**Overall Objectives**

The objectives of the project were (1) to complete our preceding effort, supported by NASA grant NAG5-11619, of searching for deep moonquakes in the far hemisphere of the Moon among the seismic events detected by the Apollo seismic array; and (2) to re-examine the distribution and mechanism of deep moonquakes in the light of the newly identified deep moonquakes.

The project was originally planned for completion in three years, of which only the first year, covered by this report, was funded. As a result, we were able to address only the first objective during the period, and the major part of the second objective was left for the future.

**Summary of Activity and Accomplishments**

Our activity during the year was concentrated on completing the search for deep moonquakes on the far side of the Moon among more than 200 newly identified groups of deep moonquakes as reported earlier [Nakamura, 2003]. Initially, we restricted our analysis to about 90 groups (deep moonquake nests) for which waveform-matched signals were available at three or more stations, and thus their hypocenters could be determined. We produced a stacked seismogram of each group at each station, read the P- and S-wave arrival times, and computed their hypocenters whenever a sufficient number of arrival picks was available. As reported at the Lunar and Planetary Science Conference last year [1], we thus identified three new deep moonquake nests on the far side, but none of them were far enough beyond the limb to provide any new information on the very deep interior of the Moon. However, the fact that all of them displayed clearly identifiable shear waves at one or more corners of the Apollo seismic array led us to the following alternate hypotheses: (1) No deep moonquakes exist within about 40° of the antipode. (2) The property of the deep interior of the Moon is such that no seismic waves can transmit through it.

We then expanded our search to include those groups which did not provide a sufficient number of arrival picks for their hypocenters to be computed, considering that such events might still render useful information on the deep interior of the Moon. We repeated the same type of analysis as above for this group of events, and this resulted in identification of about 30 nests that were likely to be on the far side. It also suggested that the second hypothesis mentioned above was more likely to be true. This result was presented at the 2004 fall meeting of AGU [2], and was recently published in JGR [3].

With the search for far-side deep moonquakes more or less completed (but see also remaining problems below), we started to examine the spatial distribution of deep moonquake hypocenters in an effort to delineate the mechanism that caused these quakes. We expected that, with the recently expanded data set including events of lesser waveform correlation, the spatial extent of hypocenters within a deep moonquake nest might be larger than what we determined earlier [Nakamura, 1978]. Starting with the  $A_1$  nest, and using the frequency derivatives of the cross-phase spectra of P- and S-wave codas, we computed the distribution of S-P arrival time differences at each station and that of S-wave arrival time differences between all possible pairs of stations. Contrary to our initial expectation, our preliminary result showed that the size of the  $A_1$  nest was still limited to at most 1 km in diameter. The question, then, is why the spatial extent did not expand when events of lower waveform correlation were included. The answer may be that, even when the source location is fixed in place, the recorded waveforms change as the slip direction rotates in a given fault plane when the tidal stress varies. This result was presented at the 36th Lunar and Planetary Science Conference [4].

We also started to collaborate with Junji Koyama of Hokkaido University to re-examine the temporal and spatial patterns of deep moonquake occurrence in relation to tidal stress inside the Moon using the recently expanded list of events. Many deep moonquake events occurring asynchronous to monthly periodicity are now recognized, and their global occurrence pattern appears to suggest that very little accumulated tectonic stress, if any, is needed to explain their occurrence [Koyama, 2005].

Finally, the support from this grant allowed the PI to continue providing assistance to and collaboration with several outside scientists, both in the U.S. and abroad, in problems related to the ALSEP (Apollo Lunar Surface Experiment Package) data. Among them are Renee Bulow and others at UCSD, Shaopeng Huang of University of Michigan, Jim Richardson of University of Arizona, Amir Khan of University of Copenhagen, Eric Larose of University of Grenoble, Philippe Lognonné of IPGP, Jürgen Oberst of DLR, and several others.

### **Remaining Problems and Tasks**

The project, as initially envisioned, is still incomplete. The following problems remain to be examined, and a proposal to continue this effort has been submitted.

Bulow *et al.* [2004, 2005] recently discovered previously uncatalogued deep moonquake events among the Apollo PSE (Passive Seismic Experiment) data set, including 101 newly identified  $A_1$  events. Although many of these events are too small to be admissible to the type of analysis described above, some may be sufficiently strong to be useful. We are currently assembling these data for analysis.

The next step will be to compute 3-D distribution of deep moonquake foci within the  $A_1$  nest based on relative S-P arrival time differences and relative S-wave arrival time differences between stations as determine above. We are currently developing a program to do this computation. Once this is done, we will examine the spatial distribution of foci within the nest to see what this distribution suggests concerning the cause and mechanism of deep moonquakes.

An interesting feature of deep moonquakes we noticed during the course of this study is the reversal of polarity of seismic waveforms from time to time. Sometimes, the polarity reversal occurs at all stations, but at other times it occurs at some stations but not at other stations. This must be explained in relation to the orientation of the tidal stress, and thus may lead to finding the real cause of these quakes.

A similar analysis needs to be performed for deep moonquake nests other than  $A_1$ . Such analysis, which has never been done before, will provide a global pattern of deep moonquake focal mechanisms and also serve as tests for deep moonquake hypotheses developed base on the  $A_1$  data. This will further extend our knowledge of the real cause of these quakes and eventually lead us to a better understanding of the nature of the deep interior of the Moon.

A better determination of the location of deep moonquake nests is a remaining problem. The 30 or so nests that have tentatively been located on the far side would be more useful if their precise locations were known. We need to continue to search for a proper method to accomplish this.

## References

- Bulow, R. C., C. L. Johnson and P. M. Shearer, Optimization of deep moonquake event stacks in the Apollo lunar seismic data and applications to the lunar structure, AGU Fall Meeting, abstract #P23A-0223, San Francisco, 2004.
- Bulow, R. C., C. L. Johnson and P. M. Shearer, Detection of new deep moonquakes in the Apollo lunar seismic data: Implications for temporal and spatial distribution, *Lunar Planet Sci. Conf.*, 36th, abstract #1581, Houston, 2005.
- Koyama, J., Chaotic occurrence of some deep moonquakes, *Lunar Planet Sci. Conf.*, 36th, abstract #1077, Houston, 2005.
- Nakamura, Y.,  $A_1$  moonquakes: Source distribution and mechanism, *Proc. Lunar Planet. Sci. Conf.*, 9th, 3589-3607, 1978.
- Nakamura, Yosio, New identification of deep moonquakes in the Apollo lunar seismic data, *Phys. Earth Planet. Interiors*, 139, 197-205, 2003.

## Publication and Abstracts

- [1] Nakamura, Y., More far-side deep moonquake nests discovered, *Lunar Planet. Sci. Conf.*, 35th, abstract #1155, Houston, March 2004.
- [2] Nakamura, Y., Deep moonquakes: Remaining problems, AGU Fall Meeting, abstract #P23A-0224, San Francisco, December 2004.
- [3] Nakamura, Y., Far-side deep moonquakes and deep interior of the Moon, *J. Geophys. Res.*, 110, E01001, doi: 10.1029/2004JE002332, 2005.
- [4] Nakamura, Y., Spatial extent of a deep moonquake nest — A preliminary report of reexamination, *Lunar Planet. Sci. Conf.*, 36th, abstract #1168, Houston, 2005.